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QUALITY OF INFORMATION METRICS FOR AUTONOMOUS DECISION MAKING

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14. ABSTRACT ***(Maximum 200 Words)***
This effort explores the management of information flows in a UAV. It is research into the information requirements for flying a UAV and how the quality of that information might be ascertained. This presentation looks at early results using information theory constructs to evaluate different information flows.

15. SUBJECT TERMS
information, UAV, quality of information, reliability

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Quality of Information Metrics for Autonomous Decision Making

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Robert Smith and Raman Mehra

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Outline

- Distributed Infocentric Reliable Control Technology (DIReCT) Program
- Quality of Information (QoI)
  - Problem statement, measure of QoI
  - Autonomous QoI computations
  - QoI Demonstration Example 1
    - Strike UAVs exchange position information for collision avoidance
    - Autonomous detection of channel changes
  - QoI Demonstration Example 2
    - Tactical ISR to Strike UAV communication of Combat ID
    - Autonomous assessment of QoI of discrete-valued data
- Conclusions and Future Work Directions

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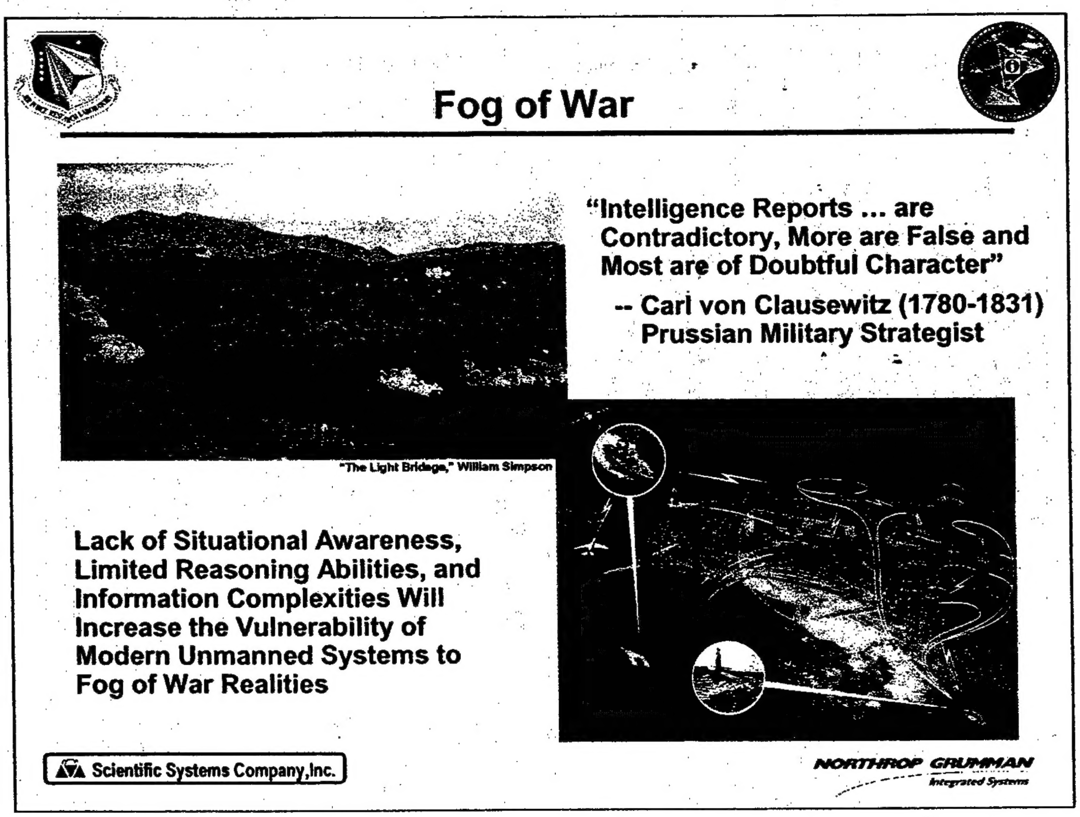

Basic story here is that unmanned systems face the same Fog of War as do any military unit and we need to account for it.

DIReCT Program Objectives

- Develop Methodologies and Architectures that Enable Single and Multi-Vehicle UCAV Systems to Manage the Information Degradation Resulting from the Fog of War
- Key Areas
  - Information Requirements
  - QoI & VoI Methodologies
  - QoI Compatible Architectures
  - QoI Degradation Opportunities

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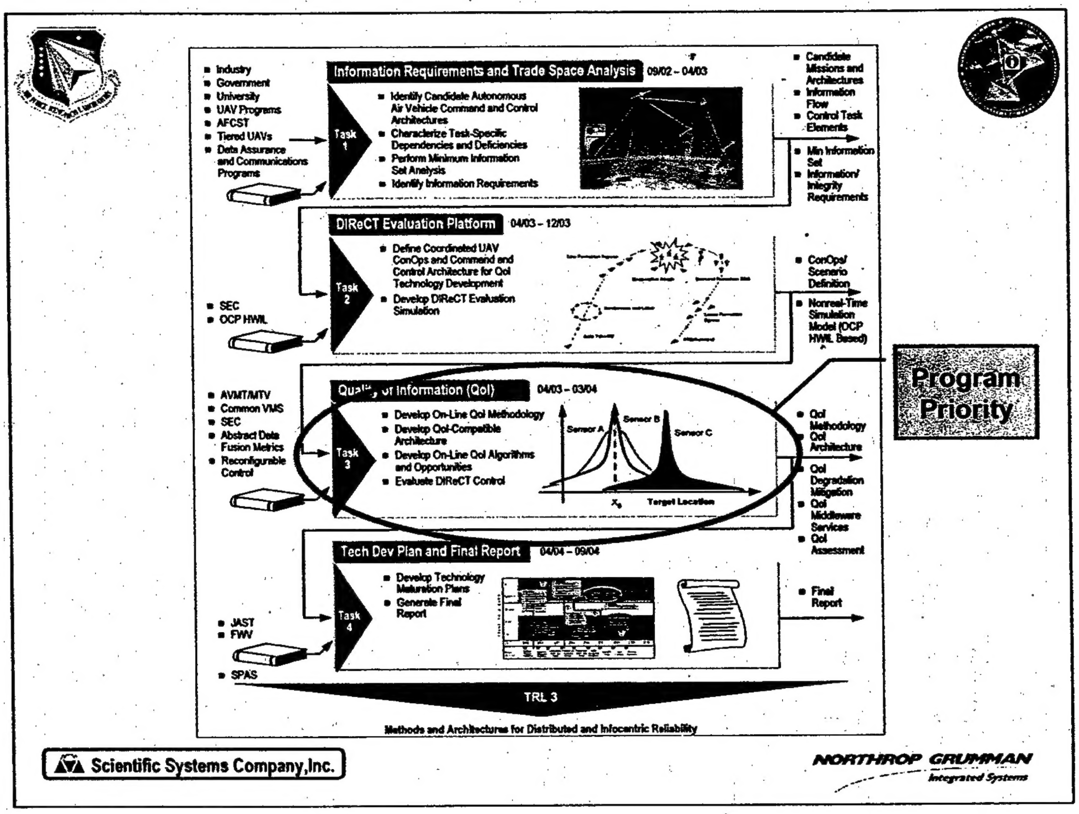
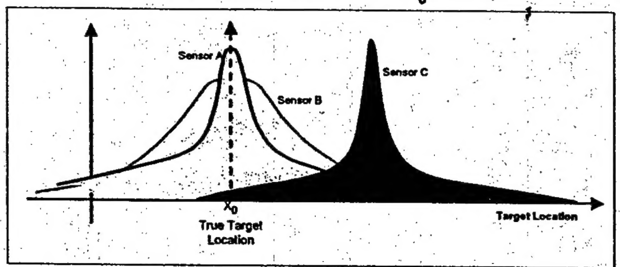
We're developing information management tools/algorithms to deal with the Fog of War.



Eye chart showing program inputs and outputs and identifying the part that will be focused on in this presentation.

Quality of Information (QoI)

- Consider three target location sensors A, B and C
- True target location is a delta function at X_0



- Which sensor is giving better quality information ?
  - Sensor A is better than Sensor B since it has lower variance
  - Sensor A is better than Sensor C even though Sensor C has lower variance because of its bias.

Desirable Property for QoI measures: If A provides information closer to ground truth than B, then QoI(A) > QoI(B)

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Basic concept of Quality of Information: many sources with different outputs, which is better?

QoI Measure – Kullback-Leibler

Kullback-Leibler (KL) Information Distance

$$K(f,g) = \int f(x)\log\left(\frac{f(x)}{g(x)}\right)dx$$

Shannon entropy is equal to -K(f,u) where u is uniform pdf

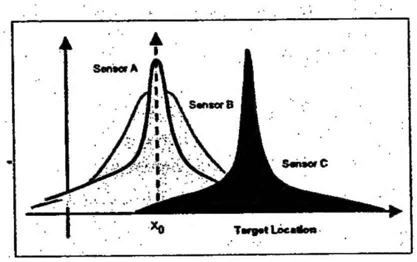
Important properties:

K measures information distance between densities, and is always greater than or equal to zero.

$$K(f,g) \geq 0$$

K is zero if and only if f(x) = g(x).

$$K(f,g) = 0 \Leftrightarrow f = g$$



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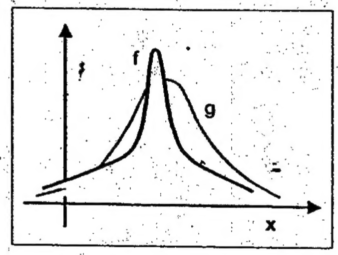
Information theory way to measure differences in probability density functions.

QoI Measure – KL Distance

- More generally, consider random variable x with pdf *f* and a sensor for x with pdf *g*
- If *g* is equal to *f*, then sensor is providing complete information.
  - *K(f,g)* is zero in this case.
- If *g* is not equal to *f*, then sensor is not providing complete information.
  - *K(f,g)* is strictly positive in this case.



When we say that a sensor is providing information of high quality, we really mean that the sensor is providing information that is close in some sense to the ground truth.

K(f,g) is a measure of the information being supplied by the sensor as compared to the ground truth f.

1/K is thus a measure of QoI

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Apply that distance measure to Quality of Information

QoI Computation

- **Suppose *f* and *g* are Gaussian:**

$$f(x)=\frac{1}{(2\pi\det P)^{n/2}}\exp\left(-\frac{1}{2}(x-a)^T P^{-1}(x-a)\right)$$

$$g(x)=\frac{1}{(2\pi\det Q)^{n/2}}\exp\left(-\frac{1}{2}(x-b)^T Q^{-1}(x-b)\right)$$

- **Then,**

$$K(f,g)=\frac{1}{2}\log\frac{\det Q}{\det P}+\frac{1}{2}Tr\left(PQ^{-1}\right)-\frac{n}{2}+\frac{1}{2}Tr\left(Q^{-1}(a-b)(a-b)^T\right)$$

- **Quadrature formulas can be used in general case.**
- **Suppose f and g are discrete probability distributions. Then, KL is just a sum:**

$$K(f,g)=\sum_{k=1}^{N} f_k \log\left(\frac{f_k}{g_k}\right)$$

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One way to implement the measure

Family of QoI Measures

- General form of information distance measures (Csiszar, 1967)

$$d(p_1, p_2) = g\left(E_{p_1}\left[f\left(\frac{p_2}{p_1}\right)\right]\right)$$

f convex, *g* increasing and *E* denotes expectation

- Some special cases that will be considered

Variational Distance

$$f(x) = |1-x|,\ g(x) = x/2$$

$$d(p_1, p_2) = \frac{1}{2}\int |p_1(x) - p_2(x)|\,dx$$

KL Information

$$f(x) = -\log x,\ g(x) = x$$

KL Divergence

$$f(x) = (x-1)\log x,\ g(x) = x$$

Bhattacharyya Distance

$$f(x) = -\sqrt{x},\ g(x) = -\log(-x)$$

$$d(p_1, p_2) = -\log\left(\int \sqrt{p_1(x)p_2(x)}\,dx\right)$$

Chernoff Distance

$$f(x) = -x^{1-r},\ g(x) = -\log(-x),\ 0 \le r \le 1$$

$$d(p_1, p_2) = -\log\left(\int p_1(x)^r p_2(x)^{1-r}\,dx\right)$$

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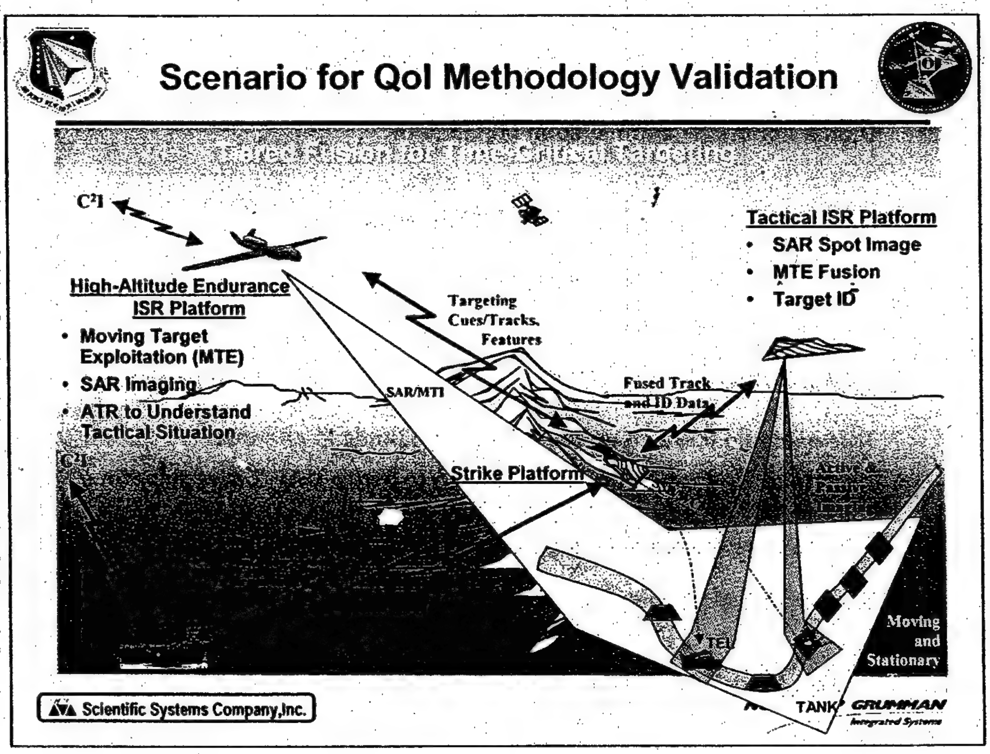
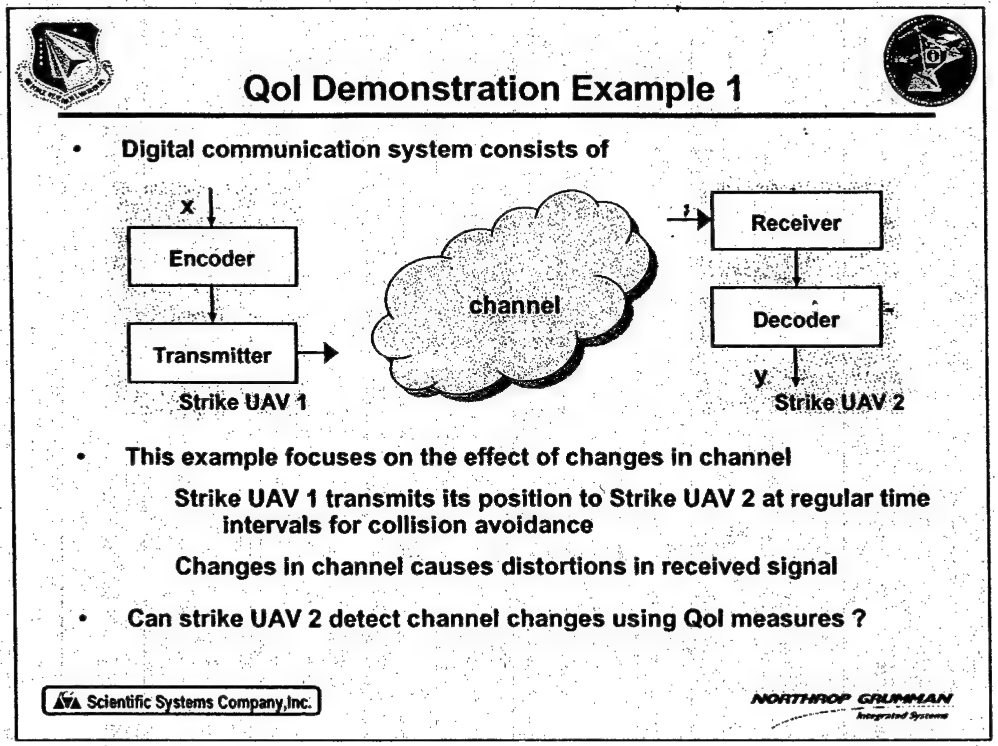
Several approaches to measuring information distance.



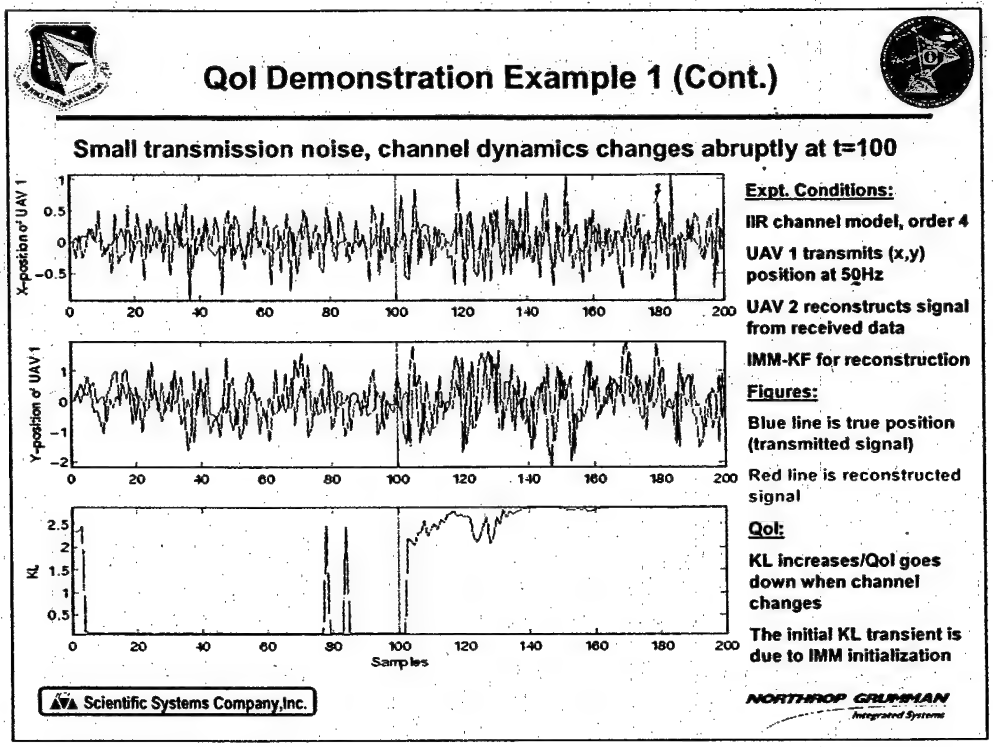
Challenging information scenario

-tiered: multiple levels and sources of information

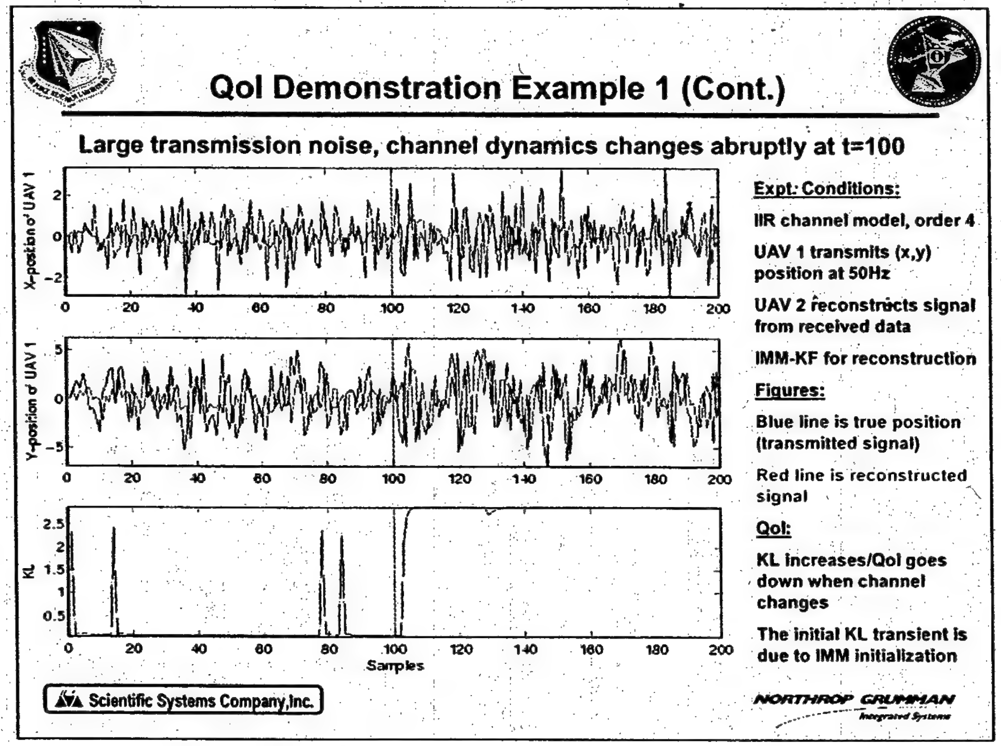
-Time-critical: timeliness is an important factor



How might these concepts be applied to a simple communication system



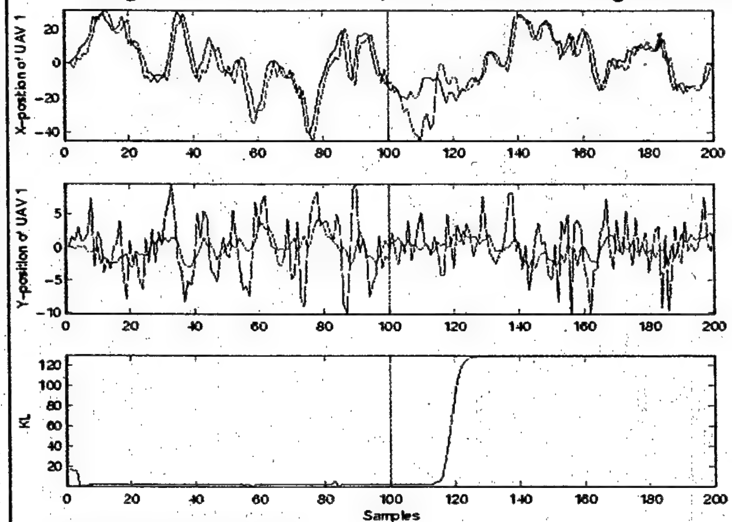
Simulation data showing measurement of QoI when comm channel degrades



Simulation data showing measurement of QoI when comm channel degrades

QoI Demonstration Example 1 (Cont.)

Large transmission noise, slow channel change starts at t=100



Expt. Conditions:

IIR channel model, order 4

UAV 1 transmits (x,y) position at 50Hz

UAV 2 reconstructs signal from received data

IMM-KF for reconstruction

Figures:

Blue line is true position (transmitted signal)

Red line is reconstructed signal

QoI:

KL increases/QoI goes down when channel changes

Small delay in detecting change

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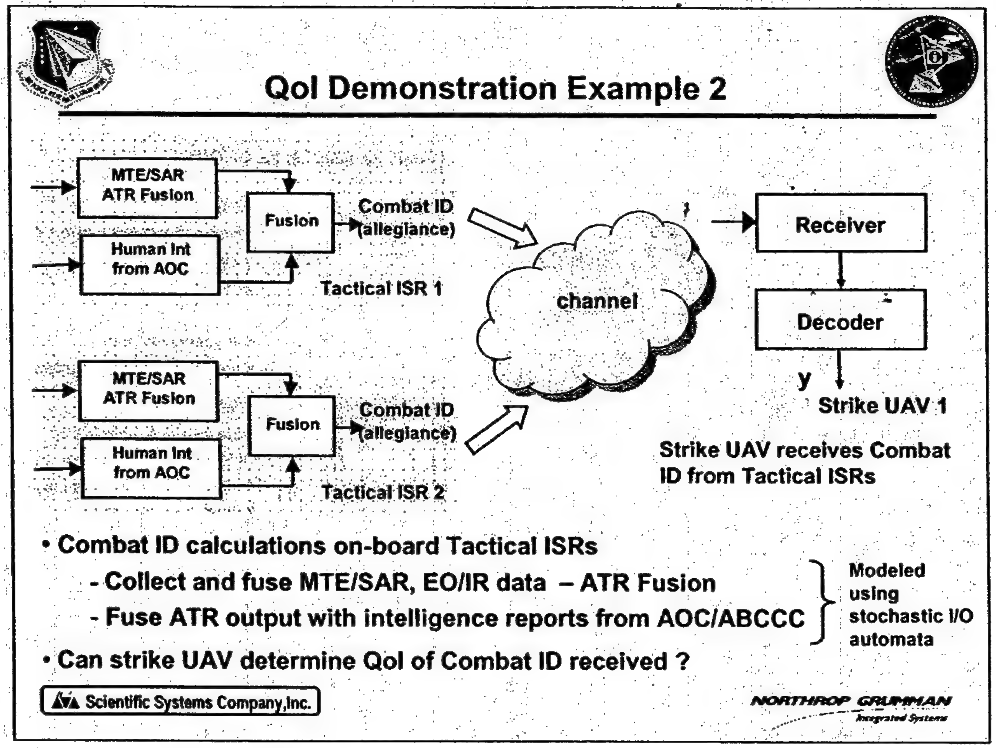
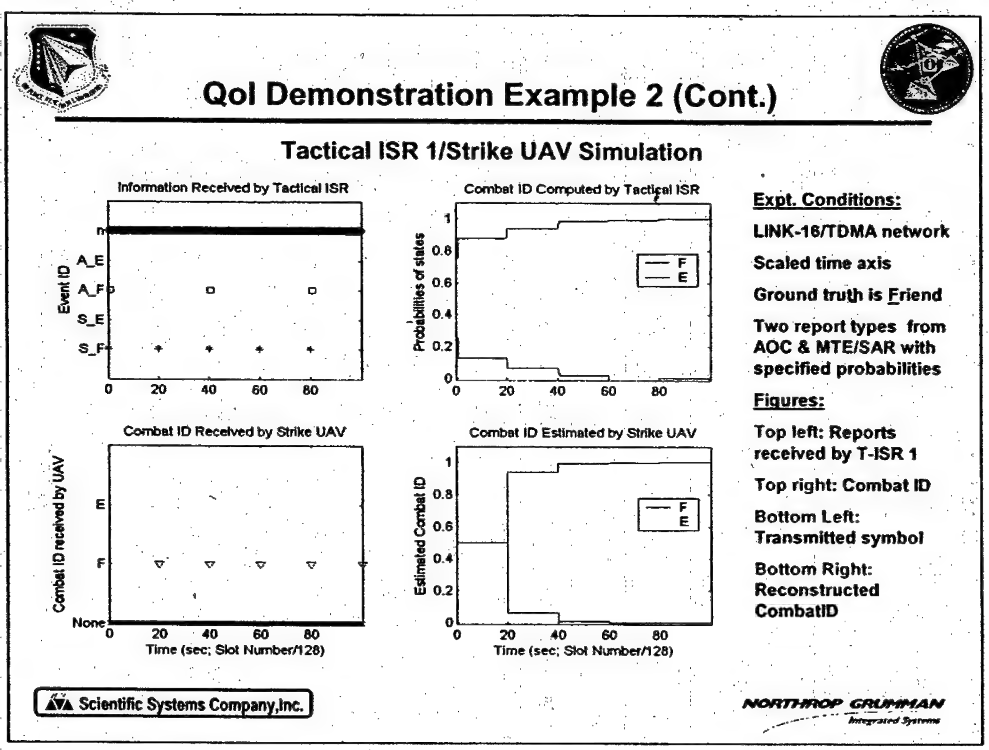
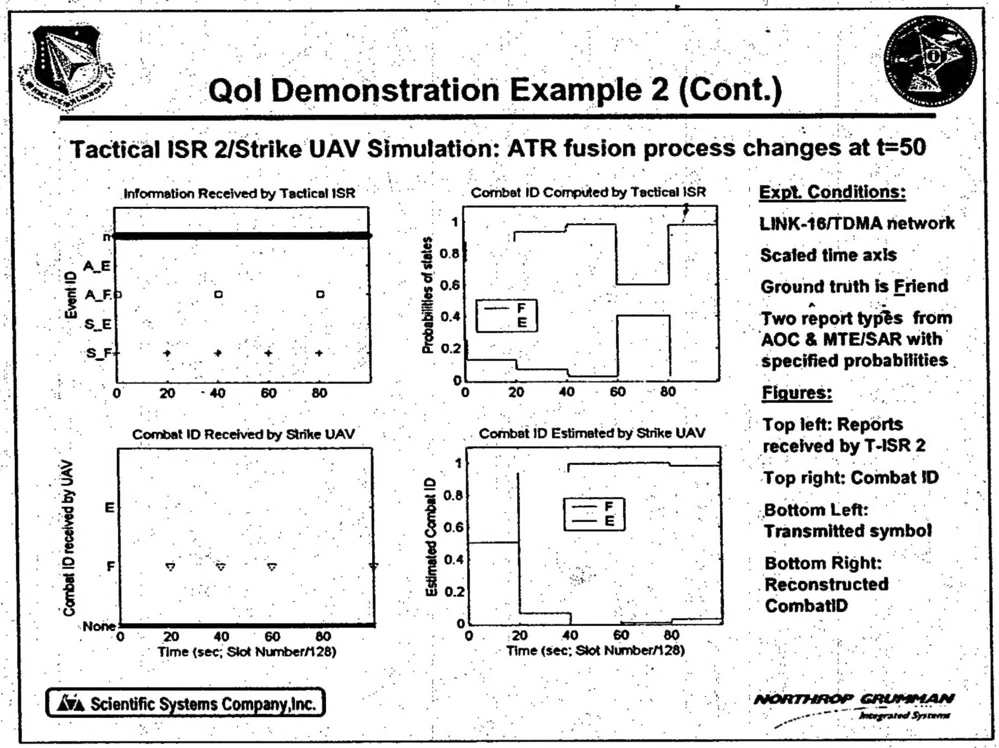
Simulation data showing measurement of QoI when comm channel degrades



Two sources of combat identification (friend/foe); what is the value of each?



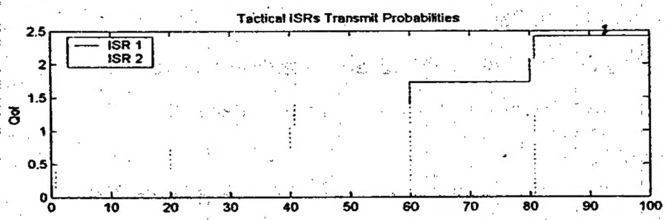
Simulation results: reconstructing from intermittent information

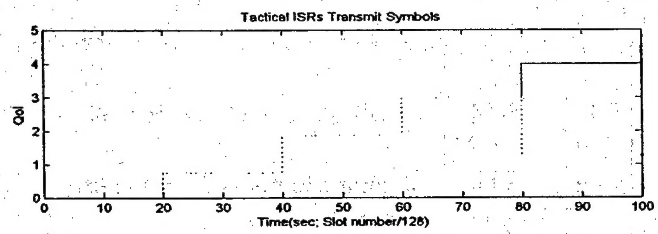


Simulation results: reconstructing from intermittent information with a dropout

QoI Demonstration Example 2 (Cont.)

Tactical ISR 2/Strike UAV Simulation: ATR fusion process changes at t=50





Top Figure:

T-ISRs transmit Combat ID probabilities

Compare each distribution with uniform distribution

QoI decreases with jump in ISR 2

Bottom Figure:

T-ISRs transmit Combat ID symbols (F or E)

Reconstruct probabilities with Bayes filter

Comapre reconstructed distributions with uniform

QoI decreases with jump in ISR 2

Time delays in detection due to low sampling rate

Better to transmit probabilities than to reconstruct them at strike UAV

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Conclusions

- Developed a procedure to autonomously determine QoI of received data.
    - Uses Kullback-Leibler information distance
    - A family of measures applicable to different tasks/missions
    - Applicable to both real-valued and discrete-valued data
- Demonstrated applicability to
    - real-valued data communication between UAVs in a strike package for collision avoidance
    - Combat ID calculation and communication between AOC/Tactical ISR and strike UAV
- QoI methodology is capable of detecting changes in channel as well as the source characteristies.
    - There is some time delay in detecting changes because of the low number of Combat ID measurements (received data)

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Future Work

- Detailed modeling of accrual of evidence by Tactical-ISRs
  - How long does it take to bring probability of correctly identifying target as foe above 0.9999999 or reducing false alarm probability to less than 10^{-6} ?
  - How to reduce identification time (hence, overall delay) using communication among Tactical-ISRs, multiple looks, etc ?
  - How to incorporate "rules of engagement" into QoI framework ?
- Detailed modeling of comm. failure mechanisms and their effects on QoI
- Demonstration of QoI methodology on a realistic mission simulation

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